Optimal Combining Data for Improving Ocean Modeling

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Award N00014-11-1-0369
http://www.onr.navy.mil/sci_tech/ocean/onrpgahm.htm

LONG-TERM GOALS

The long range scientific goals of the proposed research comprise: (1) developing rigorous approaches to optimal combining different kinds of data (images, CTD, HFR, glider, drifters , and possibly output of regional circulation models) for accurate estimating the upper ocean velocity field, subsurface thermohaline structure, and mixing characteristics (2) constructing computationally efficient and robust estimation algorithms based on alternative parameterizations of uncertainty and comprehensive testing them on synthetic data (3) processing real data collected in coastal zones via new techniques

OBJECTIVES

The objectives for the last year of research were: (1) Testing an earlier developed method for fusing ADCP data with CTD profiles on real data . (2) Developing and testing an algorithm of combining two tracer observations with HFR data for estimating surface velocities. (3) Theoretical studing finite time Lyapunov exponent (FTLE) to lay a ground for estimating it from observations.

APPROACH

We develop theoretical approaches to the data fusion problem in context of the possibility theory (fuzzy logic) and in the framework of the classical theory of random processes and fields covered by stochastic partial differential equations. We also design computational algorithms derived from the theoretical findings. A significant part of the algorithm validation is their testing via Monte Carlo simulations. Such an approach provides us with an accurate error analysis. Together with my collaborators from Rosenstiel School of Marine and Atmospheric Research (RSMAS), Consiglio Nazionale delle Ricerche (ISMAR, LaSpezia, Italy), University of Toulon (France), Observatoire Oceanologique de Villefranche sur Mer (France), and Naval Postgraduate School (Monterrey, CA) we implement the algorithms in concrete ocean models such as HYCOM, NCOM, MFS, and NEMO as well as carry out statistical analysis of real data sets by means of new methods

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Optimal Combining Data for Improving Ocean Modeling**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Southern California,Center of Applied Mathematical Sciences,3620 Vermont Avenue,Los Angeles,CA,90089-2532**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

1. Testing an earlier developed method for fusing ADCP data with CTD profiles on real data.
The problem of fusing ADCP velocity measurements and CTD data can be formulated as a two objective optimization non-linear problem with a large number of free parameters. Concerning with stability of the corresponding algorithm and accounting for some exactly solved examples elaborated by ourselves we have selected a genetic algorithm (GA) based on a derivative-free search method from [1,2]. This algorithm (neighborhood algorithm) is able to solve highly nonlinear and non-local optimization problems [3,4]. Note that the procedure can be also realized very efficiently on a multi-processor computer because each non-dominated solution for the Pareto optimal is searched separately. We have fused ADCP and CTD data collected in NAVOCEANO shipboard survey based upon the California Cooperative Fisheries Investigations protocol between 1997 and 2007, and Argo float data in the California Current System [5].

2. Developing and testing an algorithm of combining two tracer observations with HFR data for estimating surface velocities
We suggested and verified a method of combining observations of two tracers on the sea surface such as temperature and salinity, or temperature and color, with measurements from a single HF radar to estimate the underlined surface circulation. Uncertainties in transport equations for the tracers (due to poor knowledge of sources and sinks) are modeled in spirit of fuzzy logic ideas, i.e. without statistical description of errors. A similar approach we used earlier in estimating surface velocities by combining a single tracer data and model output [6,7].

The developed procedure was tested on two synthetic velocity fields representing a regular eddy system and a coastal circulation respectively.

3. Theoretical studing finite time Lyapunov exponent (FTLE) aimed at estimating it from observations
The finite time Lyapunov exponent, FTLE, first suggested in [8], is a scalar value which characterizes the amount of stretching along a Lagrangian trajectory over a certain time interval. For most flows of practical and theoretical importance, the FTLE is a function of space and time. Thus, considering FTLE as a field provides important knowledge on the variability of a flow mixing properties in space and time. Originally, FTLE was efficiently used for detecting and characterizing Lagrangian coherent structures in a variety of turbulent flows, e.g. [9]. Recently, FTLE derived from tracer images has been successfully applied to an analysis of the oceanic circulation [10].

To prepare a theoretical basis for estimating FTLE from drifter and tracer observations we found exact expressions of FTLE for a few simple stochastic flows. Properties of FTLE were compared to that of finite size Lyapunov exponent (FSLE) for the same models.

RESULTS

1. Results of combining ADCP and CTD observations are presented in Fig.1

It can be seen that although NAVOCEANO data contained considerable errors due to asynchronies in the data collection, we have fairly reconstructed principal circulation patterns. A physically important result is that many of retrieved eddies turned out to live in rather shallow water, not deeper than ~ 150 m.

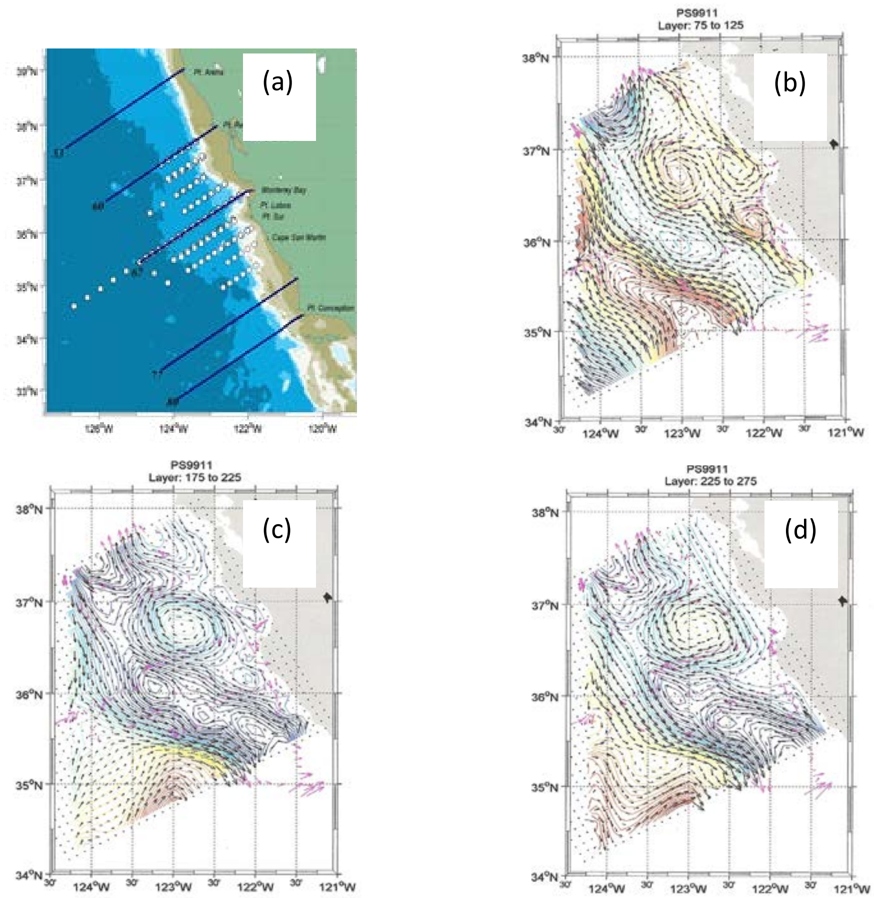

Figure1. Reconstruction of circulation from NAVOCEANO data on November, 1999. (a) Measurement stations. White stations were used for the reconstruction process. (b),(c),and (d) are reconstruction results within different layer: 25 m -75 m; 175m-225 m, and 225 m – 275 m. These results show that using fuzzy sets for parameterization of uncertainty in data allows obtaining quite reasonable results.

As for the methodology we underscore that compared to traditional assimilation techniques (OI, 4D-Var, Kalman filtering and others), the suggested approach does not require a priori knowledge on statistical weights for least square estimates. A single-objective metrics used by oceanographers is typically introduced through statistical weights, which are subjectively assigned . Naturally, this does not add accuracy to an ocean state estimate but rather introduce arbitrariness in the estimate. In practice, it is not possible to obtain these weights based on observational data only. Using fuzzy sets allows for fusing incomparable data, i.e. data or pieces of the same data which contradict one to another due to different resolution or bias. In general developed algorithms had low cost, high reliability and ease of use.

2. Results of testing the tracer/HR data fusion algorithm are presented in three figures below. In Fig.2 we show one of the experiments with a synthetic regular eddy system , where adding the radar observations reduces the error more than twice

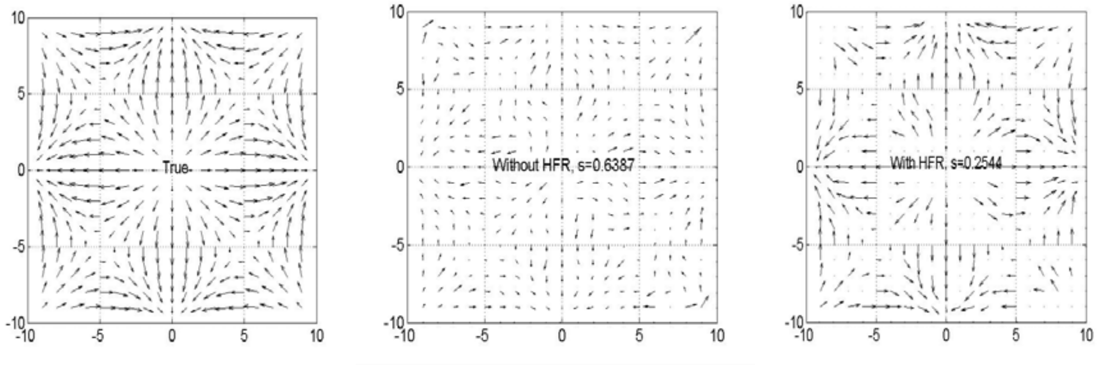

Figure 2. Left: 'True' velocity field. Center: Estimate based on the tracer observations only. Right: Estimate based on both, tracer observations and radar measurements.

As one can see adding radar measurement to observations of the tracer fields essentially improves the velocity estimates and in fact gives a perfect idea on the true circulation. Similar conclusions on including radar observations can be drawn from an error analysis when varying the unknown flux intensities. In Fig.3 we show dependence of the error on std σ of the unknown tracer forcings and the angle between lines of initial tracer fields α. The dependence on α may be significant especially in the presence of radar. If it is too small then the estimation error can dramatically increase. In variety of other experiments with the same velocity field but with different parameters it was observed that adding radar data leads to a significant decrase in error especially for small sources intensity σ.

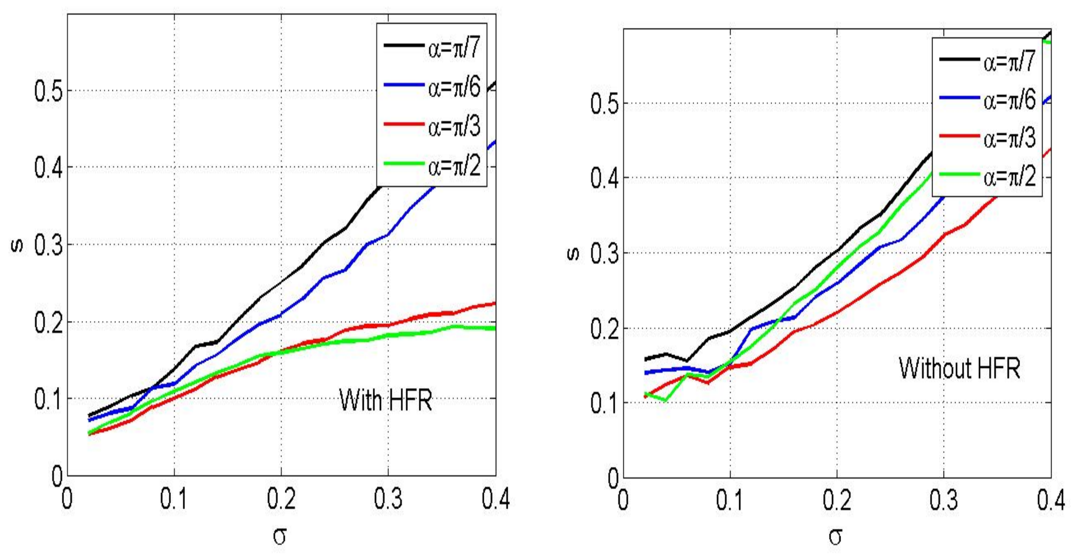

Figure 3. Left: Dependence of the estimation error on the intensity ofunknown fluxes (in presence of radar). Right: Same with no radar.

Finally, we tested the algorithm on a velocity field immitating the Bodega Bay circulation (Fig.4). Conclusions remain the same: adding a radar makes the estimate to be essentially more accurate.

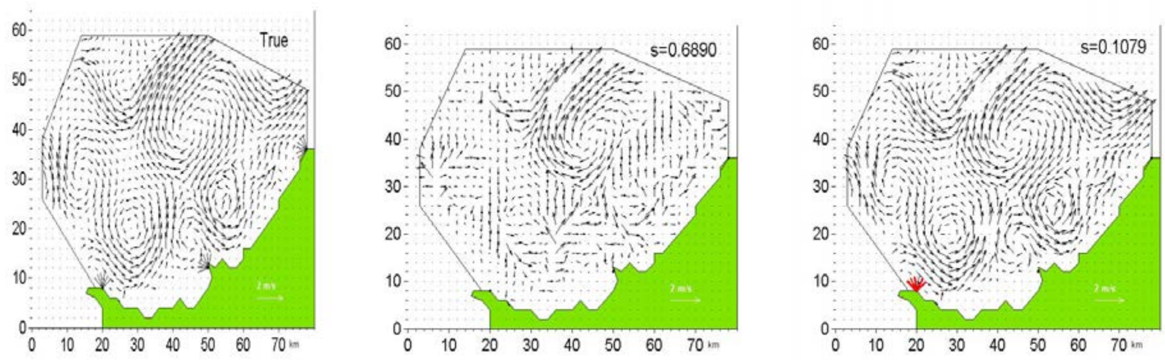

Figure 4. Left: True velocity field). Center: Estimate based on the tracer observations only. Right: Estimate based on both, tracer observations and radar measurements.

3. For a few simple stochastic models FTLE and FSLE have been exactly found and compared one to another. It was shown that for a multiplicative noise FTLE is preferable since in this case FSLE is simply zero, while the former efficiently detects the convergence and divergence regions. There is another benefit from considering FTLE: the Lyapunov exponent itself for certain nonlinear models can be derived from FTLE rather than from FSLE since there is no any closed equation for FSLE in inhomogeneous environments.

In particular, our consideration of the Kraichnan turbulence revealed that both FTLE and FSLE asymptotically (large time or small initial separation) converge to LE which was taken to be 1 (Fig. 5), but FSLE is much smoother simply because it is based on the averaging while FTLE appeals to a sample trajectory.

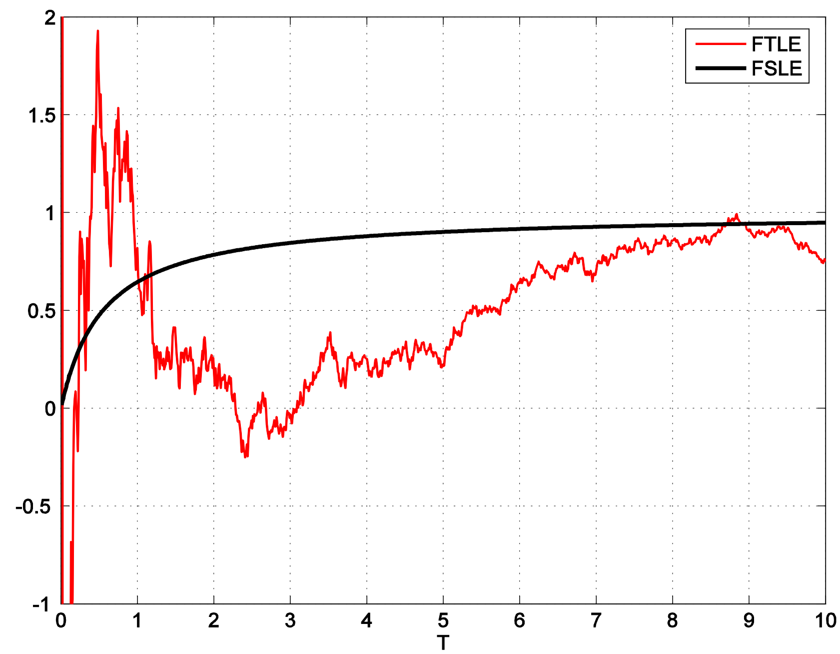

Figure 5. Comparison of FTLE and FSLE for the Kraichnan model of turbulence

IMPACT/APPLICATIONS

The developed approaches to combining ADCP and CTD observations as well as fusing tracer and radar data provide the physical oceanography community with useful tools for adequate interpreting data collected by platforms of different nature at different resolution . As a consequence , that could lead to improving diagnosis and prediction of meso- and submesoscale processes in coastal frontal zones.

RELATED PROJECTS

"Ocean 3D+", MURI Project, ONR N00014-11-1-0087, PIs: A. Griffa, T. Ozgokmen, I. Mezic, C. Jones , I. Rypina, S. L. Smith, L. Pratt, D. Kirwan

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